Photocatalytic Cell Disruption of *Giardia lamblia* in a UV/TiO₂ Immobilized Optical-Fiber Reactor

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Abstract Disinfection of a waterborne pathogenic protozoa, *Giardia lamblia*, by the conventional chlorine method has been known to be difficult. An alternative disinfection has been carried out by using a UV-light illuminating optical-fiber photoreactor. Light intensity diffused from one piece of a clad-removed optical-fiber was 1–1.5 $\mu Em^{-2}s^{-1}$. Disinfection capability in a UV-light irradiated optical-fiber reactor suspended with 0.01 g TiO₂ dm^{-3} was 1.4 times that in the same reactor without TiO₂ photocatalysts. To resolve the absorption and scattering of UV light by the particles themselves as well as the difficulty of recycling particles in the slurry-type reactor, TiO₂, which was obtained by a hydrothermal method, was immobilized on clad-removed optical fibers. Such pretreatment of fiber surface resulted in an excellent transparency, which enhanced the UV light to diffuse laterally from a fiber surface. Coating time of the prepared solution by the hydrothermal method was not effective after more than two times. Disinfection capability in the TiO₂-immobilized optical-fiber reactor was 83% in 1 h at 40°C, which was slightly higher than 76% at 22°C and 68% at 10°C. Disinfection capability at 22°C increased from 74% at an initial pH of 3.4, through 76% at pH 6.5, to 87% at an initial pH of 10. Oxygen supply with air-flow rate of 5 cm³ min^{-1} did not seem to increase the disinfection capability with UV/immobilized TiO₂.

Key words: Photocatalytic disinfection, titanium dioxide, *Giardia lamblia*, optical fiber

Chlorine, chlorine dioxide, ozone, and ultraviolet radiation are used as disinfectants in water treatment facilities. Among these, chlorine has most widely been used to disinfect drinking waters, because it is simple and cheap to use and there is much information available about it.

However, toxic chlorine byproducts such as carcinogenic trihalomethanes (THMs) may be formed. Furthermore, some pathogenic viruses and bacteria, including *Campylobacter*, *Yersina*, *Mycobacteria*, or *Legionella*, and protozoan *Cryptosporidium* or *Giardia lamblia* cysts, have been known to be resistant to chlorine disinfection [7, 10, 12, 22, 28]. The life cycle of *Giardia* in humans includes a trophozoite and a cyst form. The usual habitat of the flagellated, binucleate trophozoite is the epithelial brush border of the upper two-thirds of the small intestine [19, 20]. Symptomatic giardiasis may present with a variety of signs and symptoms, including epigastric pain, diarrhea or loose stools, abdominal cramps, malaise, weight loss, and steatorrhea. Frequent outbreaks of giardiasis have occurred, resulting in an important risk to public health. Lee et al. [12] reported that 0.13% of patients in a hospital, Seoul, Korea was infected by *G. lamblia* and the average cell number of *G. lamblia* in effluents from sewage treatment facilities was found to be 7.1 cysts dm^{-3}.

Longer chlorine residence time and higher dosages in a reactor can increase the disinfection level, but this can increase THM formation. Reduction of organic matter in influent water is needed to reduce chlorine dosage, but not to allow THM formation. The use of photocatalytic oxidation to reduce organic pollutants and to increase the effectiveness of chlorine disinfection has been widely studied. When TiO₂ is illuminated with the light of wavelength less than 400 nm, an electron is promoted from the valance band to the conduction band to give an electron/hole pair. The valance band potential is positive enough to generate hydroxyl radicals at the surface, and the conduction band potential is negative to reduce molecular oxygen.

There have been reports that TiO₂ photocatalysis by the hydroxyl radicals may be a viable process for disinfection of bacteria in water treatment systems. A UV lamp, emitting radiation of 300–400 nm with coaxially wrapped TiO₂ (anatase form) fiber-glass mesh, was used in a flow-through water reactor [8]. A reduction in the concentration

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of viable organisms of 7 orders of magnitude was reported. Matsunaga and Okochi [15] reported photoelectrochemical disinfection with anatase-type TiO_2 and Pt black mixtures under metal-halide lamp irradiation: Survival ratios of *S. cerevisiae* in a batch culture of a slurry reactor were 54% and 0% and for *E. coli* 20% and 0% after treatment for 60 and 120 min, respectively.

However, disinfection of *Giardia lamblia* by using the TiO_2/UV system has not yet been tried, where the UV light is transmitted and diffused laterally from the optical fibers in the reactor. Some have reported the disinfection of *Giardia* by using ClO_2 [26] or only UV light [4, 18], but not by TiO_2/UV. Winiecka-Krusnell and Linder showed that 97.7% of viable cysts with 1×10^3 cm^{-3} were inactivated after overnight incubation in open petri-dishes with 1 mg ClO_2 dm^{-3}, close to 99.99% by the EPA recommendation [27]. Craik *et al.* reported 99% inactivation of *Giardia* at the irradiance of 0.8 mW cm^{-2} [5].

Disinfection is promoted by solid photocatalyst particles dispersed in the liquid. However, the use of such suspensions requires separation and recycling of the ultrafine catalyst from the treated liquid, which is inconvenient, time-consuming, and expensive. In addition, the depth of UV light penetration is limited, because of strong absorption by both catalysts and dissolved organic species. These problems can be avoided by immobilization of photocatalyst particles onto a fixed surface.

Light irradiation in a phtobiological reactor can be classified as internal or external. Reflector [8, 21] or optical fiber [13, 14, 15, 17, 25] has been used in the internal type to enhance the light availability: Direct delivery of light to the photocatalyst minimizes losses due to absorption and scattering by the reactor wall and solution. In the case of using optical fibers, TiO_2 has been immobilized onto inexpensive polymeric optical fibers after scratching cladding polymers to enhance lateral diffuse of the light. However, fouling due to adsorption of cells and byproducts onto scratched fiber surface could diminish the light diffusivity [9].

In this study, disinfection of *Giardia lamblia* has been tried by using an immobilized TiO_2/UV system, where clad materials of optical fibers were removed by chemicals after combustion instead of scratching, and then immobilized with TiO_2 solution obtained by a hydrothermal method.

MATERIALS AND METHODS

Microorganism and Cell Counting

The cysts of *G. lamblia* isolated from feces of a Korean patient with chronic symptomatic giardiasis were obtained from EdiT, Inc., Korea. Cell concentration was determined by the direct cell counting method with a hemacytometer under a phase contrast microscope (~1000X, CSB-HA3, Samwon Scientific Co., Seoul, Korea) with a CCD monitor

system. In order to assure the accuracy of this easy counting method, the viable cell numbers were compared with those obtained by a conventional staining method with propidium iodide [23]. The cell numbers of viable cysts stained with propidium iodide and fluoresced bright red were estimated at 545 nm with a fluorescent microscope (Axiophat 2, Carl Zeiss GmbH, Germany), which were found to be same as those with the above phase contrast microscope.

Immobilized and Non-Immobilized TiO₂

TiO_2 (P-25, Degussa, Honau, Germany) was first used as the photocatalyst in a slurry-type batch reactor, where clad-removed optical fibers were inserted into glass tubes to diffuse UV light. The average diameter of particles was 21 nm, BET surface area was 50 ± 15 m^2 g^{-1}, and the density was 3.89 gm^{-3} at 20°C.

In the second case to apply TiO_2-immobilized reactor, silicate optical fiber (FT1.0-UMT, Thorlabs, Inc., New Jersey, U.S.A.) with inside diameter of 1 mm was combusted to remove clad materials of the fiber surface and remaining hydrocarbons on the surface was then removed by immersing in the solvent (HF:EtOH=1:1) for 3 h. Clad-removed optical fibers were dip-coated with the TiO_2 solution obtained by a hydrothermal method (Fig. 1), and dried for 1 h at 100°C.
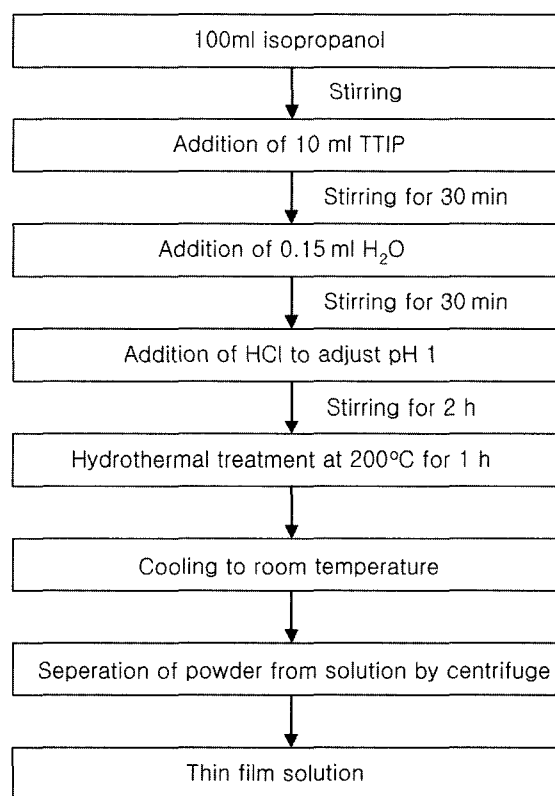

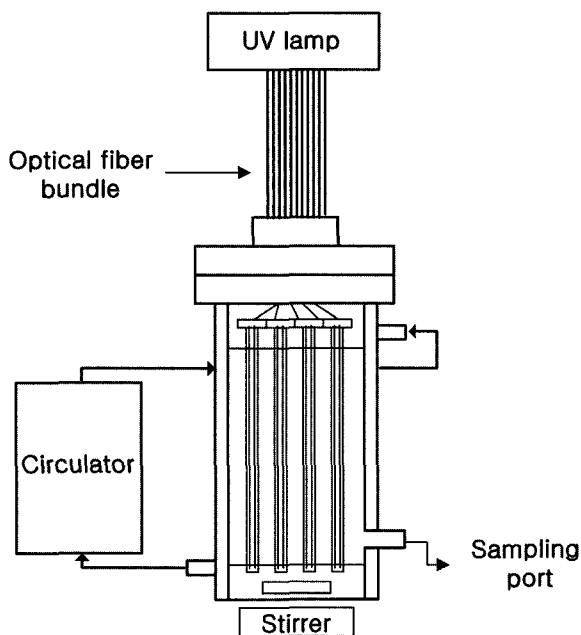**Fig. 1.** Hydrothermal process to prepare TiO_2 catalysts.

Fig. 2. Schematic diagram of an optical fiber photoreactor.

A packet of these coated silica-fibers (20 pieces) were fixed 1 cm apart with two perforated plates (each 20 holes), used as a kind of baffles, and then placed in 1.3 dm³ reactor (ID: 10 cm×H: 16 cm; Fig. 2).

Film thickness was measured with a surface profilometer (Alpha step 500, KLA Tencor Co., San Jose, CA, U.S.A.), TiO_2-film immobilized on the fiber surface was investigated by a scanning electron microscope (S-2400, Hitachi Co., Kathada, Japan), and crystalline structure and chemical composition of the film were investigated by X-ray diffractometer system (XRD, D/Max-2000, Rigaku Co., Arkansas, U.S.A.) and by FTIR (Mattson 1000, ATI Unicam, Wisconsin, U.S.A.).

Measurement of UV Light Intensity

A 400 W metal-halide lamp (Ultramed 400, Osram Co., Germany) was used as a UV light source. Its energy spectrum was measured with a monochromator (404VM, Acton Research Co., MA, U.S.A.). UV light was irradiated onto the terminal section of the inlet bundles of optical fibers by adjusting focus, and radiometric light intensity was measured with a quantum meter (Model 1000, LI-COR, Inc., Nebraska, U.S.A.).

Disinfection

Disinfection in this study was conservatively defined as a cell wall disruption due to photocatalytic action.

In a slurry type reactor, disinfections were done in an optical-fiber photoreactor, first in the absence of TiO_2 and then in the presence of 0.01 and 0.1 g TiO_2 dm⁻³ after the inoculation of *G. lamblia*. In a TiO_2-immobilized reactor,

effects of such parameters as TiO_2-coating time, reactor temperature, pH, and air-slow rate, on the disinfection capability were investigated. pH was adjusted, using 0.1 N HCl and 0.1 N NaOH solutions.

RESULTS AND DISCUSSION

Decrease of UV Light Intensity with Distance from the Fiber Surface

The energy spectrum of a UV light source used, 400 W metal-halide lamp, showed a major peak wavelength at about 375 nm with a broad spectrum in the range of 350 to 450 nm (Fig. 3). The dotted line shows the energy spectrum of the light emitted from only a piece of fiber surface, whose pattern was similar to that of the solid line.

The killing effect of UV radiation on microorganisms is primarily due to its action on DNA. The purine and pyrimidine bases of nucleic acids strongly absorb ultraviolet radiation, and the absorption maximum for DNA and RNA is at 260 nm. However, the reason of why a UV lamp emitting at 260 nm was not used in this study was that much more electric energy to emit the artificial UV light at a shorter peak wavelength is required. Furthermore, we are in a planning stage to apply the solar light in our future study, where a sensitizer is immobilized together with TiO_2 to use the visible light instead of expensive artificial UV light. The UV light intensity diffused from a piece of clad-removed optical fiber was 1 to 1.5 µE m⁻²s⁻¹. As the distance from the fiber surface increased, the UV light intensity decreased rapidly, as shown in Fig. 4.

Chemical Pretreatment of the Optical-Fiber Surface

To uniformly diffuse the UV light throughout the reactor solution, optical fibers were used. Incident light travels
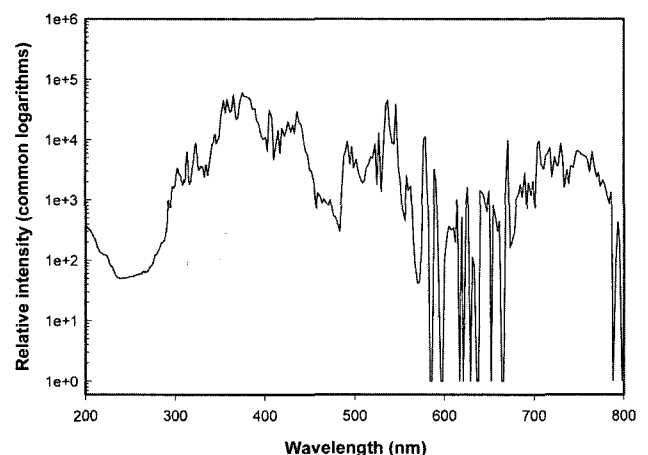

Fig. 3. Comparison of light spectrum of a 400 W metal-halide lamp and that diffused from a fiber surface, using the metal-halide lamp.
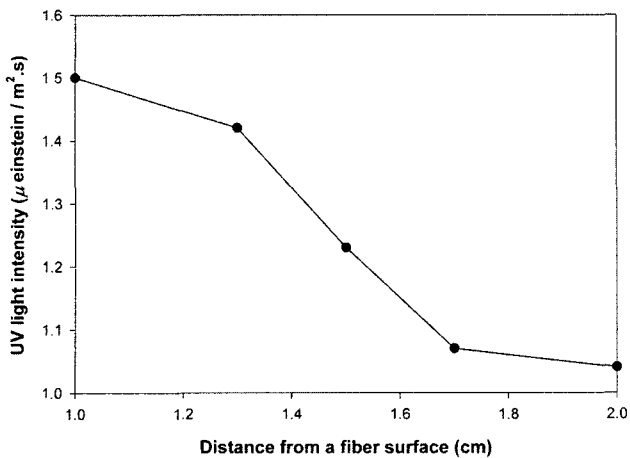
Fig. 4. Variation of quantum energy of the diffused UV light with distance from a fiber surface.

straight through a glass-fiber matrix, therefore, glass fibers are commercially produced for telecommunication. An optical-fiber surface for the telecommunication purpose is enclosed with a polymer clad for the light not to diffuse

laterally from the fiber. However, for the present study, light was required to be diffused laterally from the fiber surface, and the scratching method has been used for the removal of the clad in the case of a fiber composed of polymer core enclosed with polymer clad: In the case of a fiber composed of silicate core with polymer clad, the scratching method is not appropriate, since lateral diffusion of the light is not uniform after scratching, and byproducts can be attached on the cracks to deteriorate the light availability [9]. Therefore, the polymer clad outside of the silicate fiber was removed by combustion, and the residual hydrocarbon was then cleaned up by using the HF solvent.

Figure 5(b) shows that the residual hydrocarbon was considerably removed in the solvent of HF:EtOH (1:1 in vol) for 3 h, compared with the fiber surface obtained by the combustion (Fig. 5(a)). Figure 5(c) shows a part of the fiber (core size of 1 mm) with the surface treated by the steps (a) and (b). After pretreatment of (a) and (b), clad-removed silicate optical fibers were dip-coated with the colloidal solution of TiO_2 obtained by the hydrothermal process, as shown in Fig. 1. Relatively uniform crystal structure of TiO_2 could finally be obtained with an average
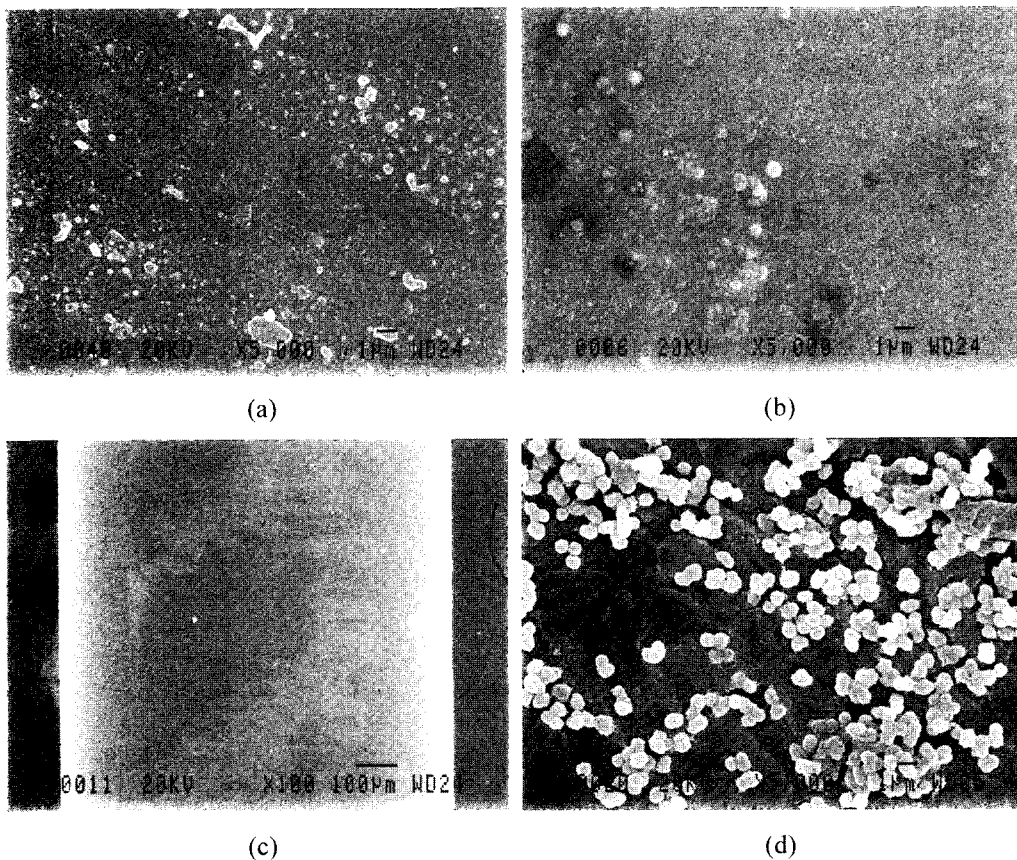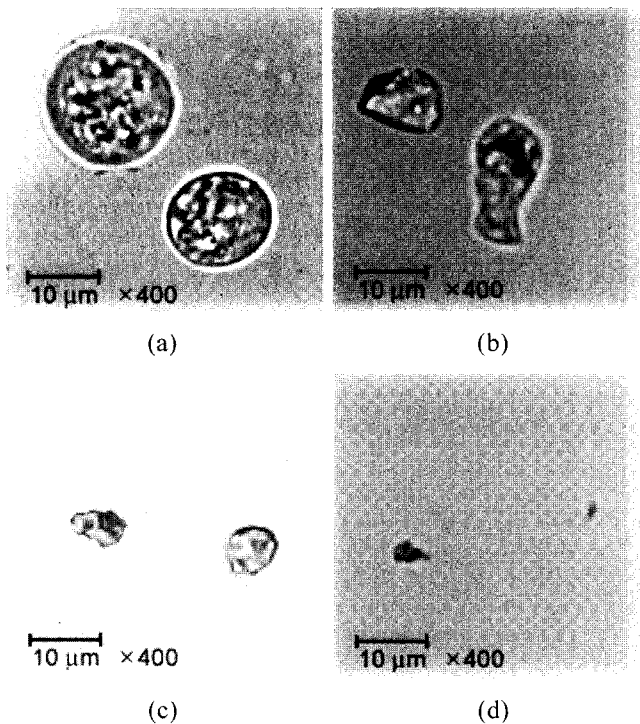

(a)

(b)

(c)

(d)

Fig. 5. SEM microscopy of a pretreated fiber surface and a TiO_2-immobilized surface.

(a) After combustion (×5,000), (b) cleaned residual hydrocarbon with HF (×5,000), (c) shown as a part of fiber with the surface treated with HF (×100), and (d) TiO_2-immobilized surface of a fiber (×5,000).

Fig. 6. Cell inactivation of *Giardia lamblia* due to photocatalytic deactivation by TiO_2/UV.

(a) Before photooxidation, (b) after 10 min, (c) after 20 min, and (d) after 30 min of exposures to TiO_2/UV, respectively.

size less than 1 μm and film thickness of 0.3–0.4 μm, which was apparently transparent.

Cell Inactivation of *G. lamblia* due to Photocatalytic Oxidation

Cell loading with the concentration of $3-5×10^5$ cell cm^{-3} was done in the photocatalytic reactor TiO_2-immobilized optical fibers. Cell lysis with time elapse is shown in Fig. 6 [4, 15, 24, 26], which was observed with a phase contrast microscope. Cell size was distinctly reduced at an initial stage, and then the shape was gradually deformed. Eventually, the cell structure was considerably diminished after 30 min exposure to TiO_2/UV.

As is well known, hydroxyl radicals produced during photocatalytic reaction of TiO_2 react with and inactivate macromolecules in the cell, of which the most important component is DNA [2]. It was reported that lipid peroxidation reaction is the mechanism underlying the death of *E. coli* when irradiated by light with a peak intensity of 356 nm in the presence of a TiO_2 photocatalyst [12]. Also, coenzyme A might be photochemically oxidized accompanied with inhibitory microbial respiration and consequent death, when the reactor vessel was illuminated together with a xenon lamp, a metal halide lamp, and a white fluorescent lamp [15]. Disinfectants reduce infectivity and/or variability before achieving cell lysis. Saito and his coworkers [23] suggested

a mechanism of the photocatalytic action against the bacteria: first, disorder of the cell membrane with rapid leakage of potassium ions and slow release of protein and DNA, and then breakdown of the cell wall with final complete destruction of the cell.

In the case of protozoan *Giardia*, unlike the vegetative form of bacterial cell described above, the life cycle includes a binucleate tropozoite (vegetative form) in a host and a cyst form in the environment. The binucleated trophozoite becomes a binucleated cyst, thereafter, each of the two nuclei within the cyst undergoes a single division to form a quadrinucleated cyst. It is assumed that this quadrinucleated cyst establishes an infection.

A cyst inactivation has been determined by a vital staining method, using propium iodide binder [4, 26]. Campbell and Wallis [1] demonstrated that the vital dye viability assays underestimate UV inactivation of *Giardia* cysts, as compared with infectivity. Estimation of a cyst inactivation based on the structural disorder in this study, which has the same results as that by the vital dye staining method (as described in the experimental section), might have also resulted in underestimation. However, overestimation of viability potential (corresponding to underestimation of inactivation) could be the most cautious approach to monitor environment as well as water treatment.

Disinfection Capability in a Suspended TiO_2 Reactor

The disinfection effect by the UV light only was investigated to obtain reference data before the application of TiO_2. Disinfection capability was about 60% in 1 h by the exposure of the UV light only. Since light absorption or scattering did not increase due to negligible production of particles and chemicals, the disinfection ratio increased linearly with the residence time.
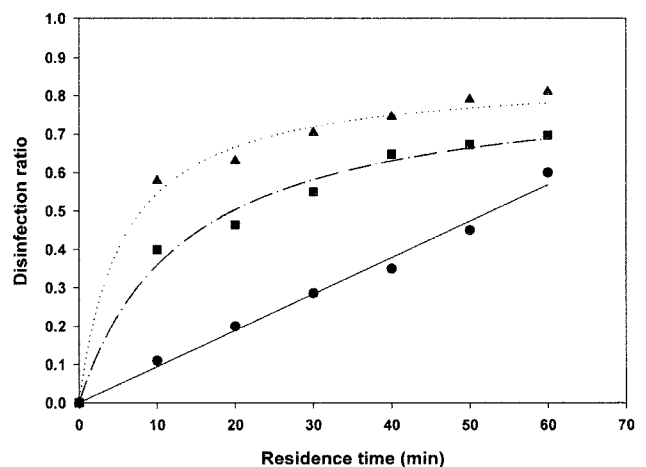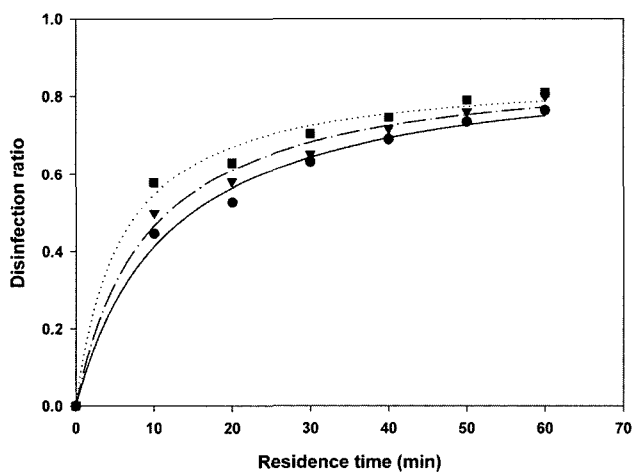

Fig. 7. Disinfection ratio of *Giardia lamblia* in an optical-fiber photoreactor (●: only the UV diffused from fibers; ▲: suspended (0.01 g TiO_2 l^{-1}); and ■: suspended (0.1 g TiO_2 l^{-1}), respectively).

However, disinfection capabilities of 58% and 38% could be obtained in 10 min, when 0.1 and 0.01 g TiO_2 dm^{-3} were suspended, respectively. Those capabilities approached slowly to 81% and 68% in 1 h after sharp increases within 10 min. Similar pattern of disinfection ratio with residence time was previously obtained for *E. coli* disinfection [3]. Light-alone experiment was previously performed in a 0.25 dm^3 batch-scale shake flask to compare the disinfection with UV/TiO_2: Time for 100% kill at the UV intensity of 10 W m^{-2} without TiO_2 was 220 min, while the time at the same light intensity with 0.1 g TiO_2 dm^{-3} was 8 min. Disinfection capability by using both TiO_2 and UV light in terms of killing time was about 27 times that obtained by the UV light only.

Since key steps of TiO_2 photocatalytic oxidation occur at the catalyst surface, the reaction rate would be expected to increase linearly with the quantity of available catalyst. At dilute TiO_2 concentrations, such relationship was observed. However, at above 0.1- 1.0 g TiO_2 dm^{-3}, the oxidation rate did not increase and approached a saturation level, as described by Langmuir-Hinshelwood kinetics [5]. In the case of TiO_2/UV disinfection, photocatalytic disinfection, but not oxidation rate, also increased to 0.1- 1.0 g TiO_2 dm^{-3}. However, the disinfection capability decreased at above 0.1- 1.0 g TiO_2 dm^{-3}, due to absorption and scattering of UV light by the suspended TiO_2 particles themselves.

Effect of TiO_2 Film Thickness on the Disinfection

The disinfection ratios with time were compared for 2- and 4-times coating of the synthesized colloidal solutions obtained by the hydrothermal method. The average diameter, the BET surface area, and the density of TiO_2 powder were 90±15 nm, 40±10 m^2 g^{-1}, and 3.95 g cm^{-3} at 20°C, respectively. The crystal structure of TiO_2 prepared by the sol-gel method

Fig. 8. Effect of TiO_2-coating time on the disinfection ratio of *Giardia lamblia* in an optical-fiber photoreactor (●: 2-times TiO_2-coating (0.343 g TiO_2 m^{-2}); ▼: 4-times TiO_2-coating (0.457 g TiO_2 m^{-2}); and ■: suspended (0.01 g TiO_2 l^{-1}), respectively).
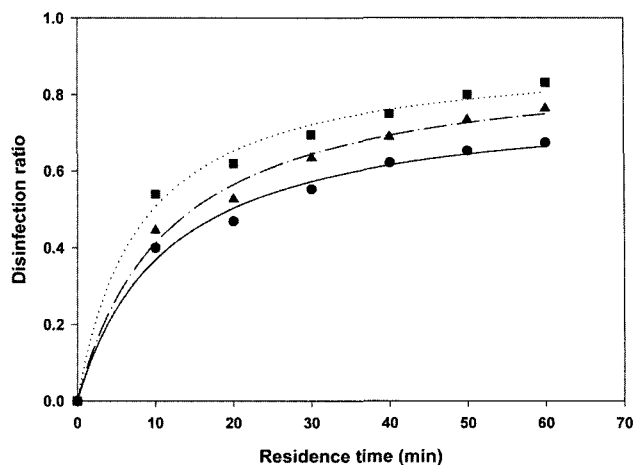
Fig. 9. Effect of temperature on the disinfection ratio of *Giardia lamblia* in an optical-fiber photoreactor (●: 10°C; ▲: 22°C; and ■: 40°C, respectively).

was the anatase type and the thicknesses of a coated film were 355, 530, and 1,180 Å, respectively, in every case of 1-, 2-, and 4-times coating. As shown in Fig. 8, the disinfection ratio with 2-times coating increased from 45% in 10 min to 76% in 1 h, whereas that with 4-times coating increased from 50% in 10 min to 80% in 1 h. Therefore, the effect of coating over two times on disinfection can be negligible in this case.

The total amount of available TiO_2 particles decreased when TiO_2 was immobilized on the optical fibers, since the fibers with sufficient piece numbers were not inserted in an immobilized reactor, correspondingly with the amount of TiO_2 in a suspended reactor. The amount of TiO_2 immobilized on the surface of optical fibers was estimated to be 0.34 and 0.46 g m^{-2} in the cases of 2- and 4-times coating, respectively. Since the lateral surface area of 16 pieces of optical fibers is $\pi(0.1/100)(16)=0.05$ (m^2), the total concentration of TiO_2 is estimated as $(0.05)(530\times10^{-8}$ $m^{-1})$ $(3.89\times10^6$ g $m^3)(m^3$ 10^3 $dm^{-3})=0.001$ g dm^{-3}, which constitutes 10% of 0.01 g TiO_2 dm^{-3} in a suspended reactor.

However, in the figure, the disinfection ratio with TiO_2-immobilized and TiO_2-suspended reactors did not significantly differ with time elapse. As expected, light absorption and scattering by TiO_2 particles themselves might have considerably been overcome by the immobilization.

Effect of Temperature on the Disinfection

The disinfection ratio at 40°C was 0.83 in 1 h, slightly higher than 0.76 at 22°C and 0.68 at 10°C. The increase of the disinfection ratio can be explained mainly by the increase of photocatalyst activity, which can be described by the Arrhenius relationship.

Even in the absence of TiO_2, the survival length of *Giardia* cysts in natural water varies greatly, depending on temperature [16]. For instance, *Giardia* cysts survive
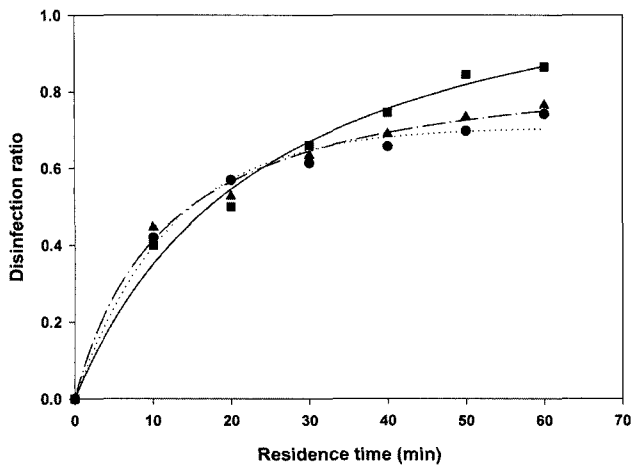
Fig. 10. Effect of pH on the disinfection ratio of *Giardia lamblia* in an optical-fiber photoreactor (●: pH 3.4; ▲: pH 6.5; ■: pH 10, respectively).
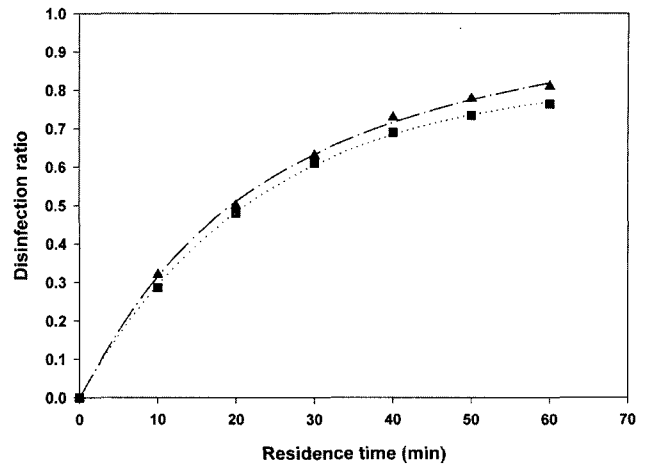

Fig. 11. Effect of air sparging on the disinfection ratio of *Giardia lamblia* in an optical-fiber photoreactor (▲: with air sparging and ■: without air sparging).

for more than two months at 8°C while they survive for about one month and four days at 21°C and 37°C, respectively.

pH Effect on the Disinfection

The effect of pH on the *Giardia* disinfection was investigated by varying the pH as 3.4, 6.5, and 10.0, and the pH was found to be not considerably high in the early stage of 10 min; the disinfection ratios were 0.42, 0.45, and 0.40 at the pH's of 3.4, 6.5, and 10.0, respectively. As time elapsed during 1 h, the disinfection ratio at pH 10.0 was shown to be 0.87, higher than 0.74 at pH 3.4 and 0.76 at pH 6.5.

Increase of disinfection with time can be explained by fact that hydroxide ion produced by the following Eq. (1) requires time to proceed the reaction of Eq. (2), since hydroxide reacts with TiO_2 particles at near diffusion-controlled rate [6]. In aqueous dispersions of TiO_2, the zeta potential was found to decrease linearly with the pH of the medium. An isoelectric point for aqueous dispersions of TiO_2 occurs at about pH=6.8 in the absence of additional solutes. The zeta potentials of TiO_2 are positive in acidic (pH<6.8) dispersions, and are negative in alkaline (pH> 6.8) dispersions, indicating positive or negative charges on the TiO_2 particles. Therefore, at pH>6.8, the TiO_2 surface is negatively charged and should repel negative ions, thus not interfering in the action of hydroxyl radicals. However, at pH<6.8, the positive charge on the TiO_2 surface attracts anions, which may considerably interfere with the hydroxylation of the organic substrates in the cell composition, resulting in the scavenging effect of OH radicals.

The positively charged holes in the surface react with water or hydroxide ions (OH⁻) within a few picoseconds to produce hydroxyl radicals (·OH), which are the primary photodisinfecting species (Eq. 1). In the alkaline solution,

OH⁻ ions will react with the positively charged holes to produce OH radicals (Eq. 2).

$$h^{+}+H_2O \rightarrow H^{+}+OH^{-} \tag{1}$$
$$h^{+}+OH^{-} \rightarrow \cdot OH \tag{2}$$

More OH radicals produced at a higher pH as time elapsed might enhance the disinfection capability.

Effect of Oxygen Supply on the Disinfection

In order to investigate the effect of O_2 supply, an air sparging rate at $5 \, cm^3 \, min^{-1}$ was investigated. As is well known, the negatively charged electrons are preferentially trapped by oxygen;

$$O_2+e^{-} \rightarrow O_2^{-} \tag{3}$$
$$O_2+2H^{+}+2e^{-} \rightarrow H_2O_2 \tag{4}$$
$$H_2O_2+e^{-} \rightarrow \cdot OH+OH^{-} \tag{5}$$

However, the disinfection ratio with air supply was 0.81, slightly higher than 0.75 without oxygen supply. In order to enhance the disinfection efficiency, air supply needs to increase with the addition of H_2O_2.

An alternative disinfection of a pathogenic protozoa, *G. lamblia*, was carried out by using the TiO_2/UV system, instead of the conventional chlorine method. Since suspended TiO_2 particles deteriorate light transmittance into a deep center region of an externally-illuminating reactor, TiO_2 particles in the reactor should be separated from the water treated. In order to solve the problem, a TiO_2-immobilized optical-fiber reactor has been adopted in which the UV light transmits and diffuses laterally from the fiber surface. The present study was focused mainly on the establishment of optimal conditions for environmental parameters such as temperature, pH, and dissolved oxygen, as well as optimal immobilization conditions in the TiO_2-immobilized system. Major results are as follows: Firstly, TiO_2-film dip-coated

with the colloidal solution prepared by the hydrothermal method showed an excellent transparency. Coating more than two times, resulting in a film thickness of 530 Å, was not effective in the disinfection capability. Secondly, disinfection capability in a UV-light illuminating reactor suspended with 0.01 g of TiO_2 dm^{-3} was 1.4 times as that in the same reactor without TiO_2 photocatalyst. Thirdly, disinfection capability in the TiO_2-immobilized optical-fiber reactor in 1 h was 83% at 40°C, 76% at 22°C, and 68% at 10°C, which were similar to those obtained with suspended TiO_2. The total amount of TiO_2 in the immobilized reactor was estimated to be 10% of that found when suspended. Lastly, as temperature increased from 10°C, through 22°C, to 40°C, disinfection capability in 1 h increased from 68%, through 76%, to 83%, respectively. As pH increased from 3.4, through 6.6, to 10.0, disinfection capability in 1 h increased from 74%, through 76%, to 87%, respectively. Apparently, disinfection capability did not increase with oxygen supply of 5 cm^3 air min^{-1} in this study. Disinfection data obtained in this study might be informative in the design of a one-through flow type UV-irradiated optical-fiber reactor.

Acknowledgment

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